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Principles of Electric Generators

2.1	The Three Types of Electric Generators.....	2-1
2.2	Synchronous Generators.....	2-4
2.3	Permanent Magnet Synchronous Generators	2-8
2.4	The Homopolar Synchronous Generator.....	2-11
2.5	Induction Generator	2-13
2.6	The Wound Rotor (Doubly Fed) Induction Generator (WRIG).....	2-15
2.7	Parametric Generators	2-17
	The Flux Reversal Generators • The Transverse Flux Generators (TFGs) • Linear Motion Alternators	
2.8	Electric Generator Applications	2-26
2.9	Summary.....	2-26
	References	2-28

The extremely large power/unit span, from milliwatts to hundreds of megawatts (MW) and more, and the wide diversity of applications, from electric power plants to car alternators, should have led to numerous electric generator configurations and controls. And, so it did. To bring order to our presentation, we need some classifications.

2.1 The Three Types of Electric Generators

Electric generators may be classified many ways, but the following are deemed as fully representative:

- By principle
- By application domain

The application domain implies the power level. The classifications by principle unfolded here include commercial (widely used) types together with new configurations, still in the laboratory (although advanced) stages.

By principle, there are three main types of electric generators:

- Synchronous ([Figure 2.1](#))
- Induction ([Figure 2.2](#))
- Parametric, with magnetic anisotropy and permanent magnets ([Figure 2.3](#))

Parametric generators have in most configurations doubly salient magnetic circuit structures, so they may be called also doubly salient electric generators.

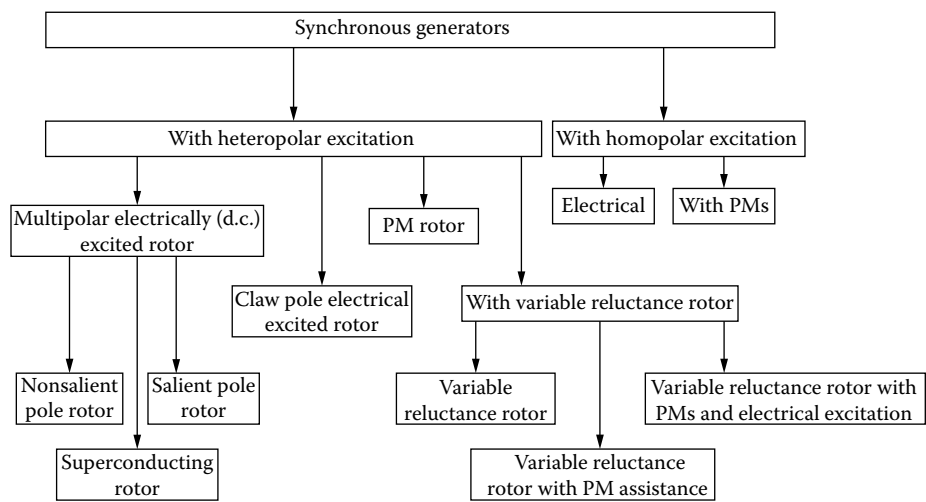


FIGURE 2.1 Synchronous generators.

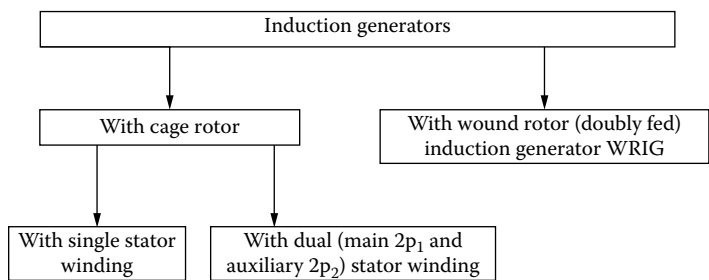


FIGURE 2.2 Induction generators.

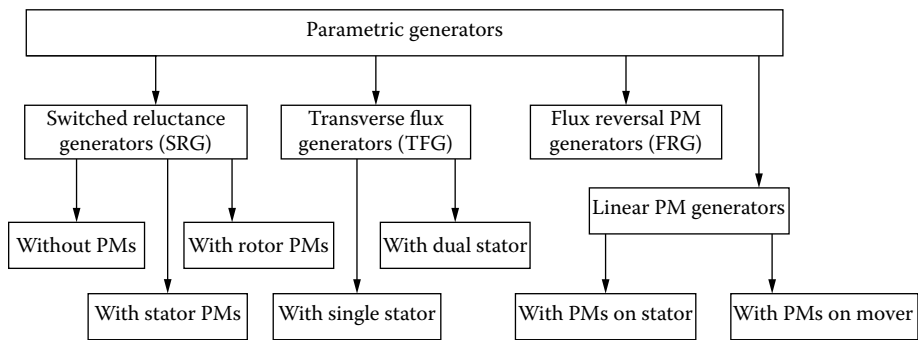


FIGURE 2.3 Parametric generators.

Synchronous generators [1–4] generally have a stator magnetic circuit made of laminations provided with uniform slots that house a three-phase (sometimes a single or a two-phase) winding and a rotor. It is the rotor design that leads to a cluster of synchronous generator configurations as seen in Figure 2.1.

They are all characterized by the rigid relationship between speed n , frequency f_1 , and the number of poles $2p_1$:

$$n = \frac{f}{p_1} \quad (2.1)$$

Those that are direct current (DC) excited require a power electronics excitation control, while those with permanent magnets (PMs) or variable reluctance rotors have to use full-power electronics in the stator to operate at adjustable speeds. Finally, even electrically excited, synchronous generators may be provided with full-power electronics in the stator when they work alone or in power grids with DC high-voltage cable transmission lines.

Each of these configurations will be presented, in terms of its principles, later in this chapter.

For powers in the MW/unit range and less, induction generators (IGs) were also introduced. They are as follows (Figure 2.2):

- With cage rotor and single stator-winding
- With cage rotor and dual (main and additional) stator-winding with different number of poles
- With wound rotor

Pulse-width modulator (PWM) converters are connected to the stator (for the single stator-winding and, respectively, to the auxiliary stator-winding in the case of dual stator-winding).

The principle of the IG with single stator-winding relies on the following equation:

$$f_1 = p_1 n + f_2 \quad (2.2)$$

where

$f_1 > 0$ = stator frequency

$f_2 < 0$ = slip (rotor) frequency

n = rotor speed (rps)

The term f_2 may be either positive or negative in Equation 2.2, even zero, provided the PWM converter in the wound rotor is capable of supporting a bidirectional power flow for speeds n above f_1/p_1 and below f_1/p_1 .

Notice that for $f_2 = 0$ (DC rotor excitation), the synchronous generator operation mode is reobtained with the doubly fed IG.

The slip S definition is as follows:

$$S = \frac{f_2}{f_1} \triangleleft 0 \quad (2.3)$$

The slip is zero, as $f_2 = 0$ (DC) for the synchronous generator mode.

For the dual stator-winding, the frequency–speed relationship is applied twice:

$$\begin{aligned} f_1 &= p_1 n + f_2; p_2 > p_1 \\ f'_1 &= p_2 n + f'_2 \end{aligned} \quad (2.4)$$

So, the rotor bars experience, in principle, currents of two distinct (rather low) frequencies f_2 and f'_2 . In general, $p_2 > p_1$ to cover lower speeds.

The PWM converter feeds the auxiliary winding. Consequently, its rating is notably lower than that of the full power of the main winding, and it is proportional to the speed variation range.

As it may also work in the pure synchronous mode, the doubly fed IG may be used up to the highest levels of power for synchronous generators (400 MW units have been in use for some years in Japan) and a 2×300 MW pump storage plant is now commissioned in Germany.

On the contrary, the cage-rotor IG is more suitable for powers in the MW and lower power range.

Parametric generators rely on the variable reluctance principle, but may also use PMs to enhance the power and volume and to reduce generator losses.

There are quite a few configurations that suit this category, such as the switched reluctance generator (SRG), the transverse flux PM generator (TFG), and the flux reversal generator (FRG). In general, the principle on which they are based relies on coenergy variation due to magnetic anisotropy (with or without PMs on the rotor or on the stator), in the absence of a pure traveling field with constant speed (f_i/p), so characteristic for synchronous and IGs (machines).

2.2 Synchronous Generators

Synchronous generators (classifications are presented in Figure 2.1) are characterized by an uniformly slotted stator laminated core that hosts a three-, two-, or one-phase alternating current (AC) winding and a DC current excited, or PM-excited or variable saliency, rotor [1–5].

As only two traveling fields — of the stator and rotor — at relative standstill interact to produce a rippleless torque, the speed n is rigidly tied to stator frequency f_1 , because the rotor-produced magnetic field is DC, typically heteropolar in synchronous generators.

They are built with nonsalient pole, distributed-excitation rotors (Figure 2.4) for $2p_1 = 2, 4$ (that is, high speed or turbogenerators) or with salient-pole concentrated-excitation rotors (Figure 2.5) for $2p_1 > 4$ (in general, for low-speed or hydrogenerators).

As power increases, the rotor peripheral speed also increases. In large turbogenerators, it may reach more than 150 m/sec (in a 200 MVA machine $D_r = 1.2$ m diameter rotor at $n = 3600$ rpm, $2p_1 = 2$, $U = \pi D_r n = \pi \times 1.2 \times 3600/60 > 216$ m/sec). The DC excitation placement in slots, with DC coil end connections protected against centrifugal forces by rings of highly resilient resin materials, thus becomes necessary. Also, the DC rotor current airgap field distribution is closer to a sinusoid. Consequently, the

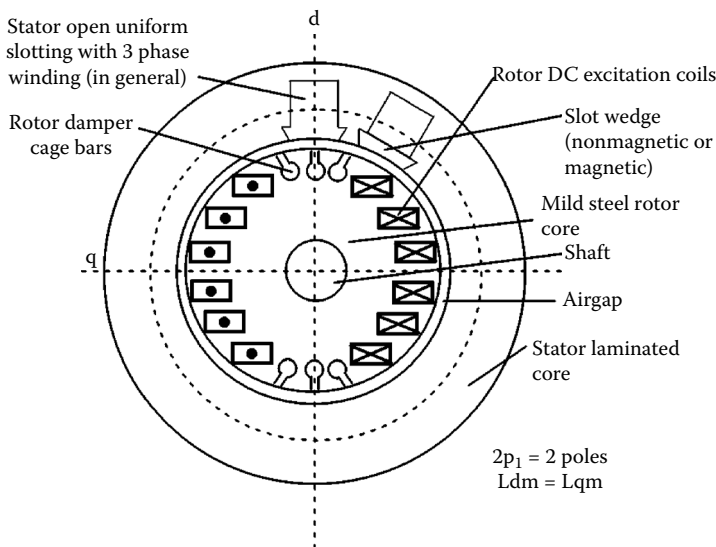


FIGURE 2.4 Synchronous generator with nonsalient pole heteropolar DC distributed excitation.

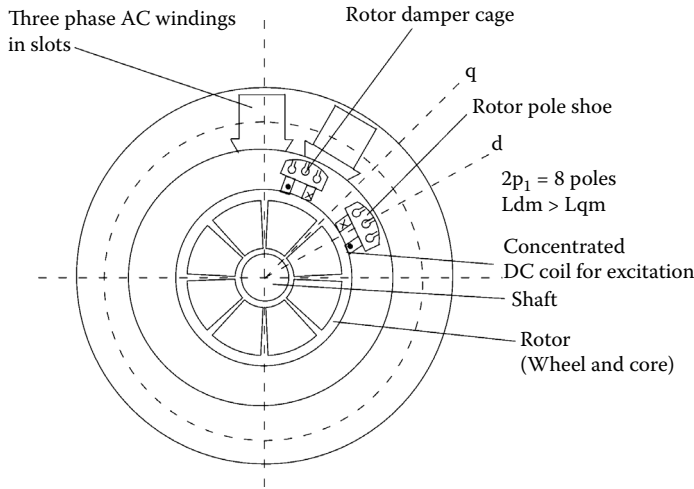


FIGURE 2.5 Synchronous generator with salient pole heteropolar DC concentrated excitation.

harmonics content of the stator-motion-induced voltage (electromagnetic force or no load voltage) is smaller, thus complying with the strict rules (standards) of large commercial power grids.

The rotor body is made of solid iron for better mechanical rigidity and heat transmission.

The stator slots in large synchronous generators are open (Figure 2.4 and Figure 2.5), and they are provided, sometimes, with magnetic wedges to further reduce the field space harmonics and thus reduce the electromagnetic force harmonics content and additional losses in the rotor damper cage. When $n = f_1/p_1$ and for steady state (sinusoidal symmetric stator currents of constant amplitude), the rotor damper cage currents are zero. However, should any load or mechanical transient occur, eddy currents show up in the damper cage to attenuate the rotor oscillations when the stator is connected to a constant frequency and voltage (high-power) grid.

The rationale neglects the stator magnetomotive force space harmonics due to the placement of windings in slots and due to slot openings. These space harmonics induce voltages and thus produce eddy currents in the rotor damper cage, even during steady state.

Also, even during steady state, if the stator phase currents are not symmetric, their inverse components produce currents of $2f_1$ frequency in the damper cage. Consequently, to limit the rotor temperature, the degree of current (load) unbalance permitted is limited by standards. Nonsalient pole DC excited rotor synchronous generators are manufactured for $2p_1 = 2, 4$ poles high-speed turbogenerators that are driven by gas or steam turbines.

For lower-speed synchronous generators with a large number of poles ($2p_1 > 4$), the rotors are made of salient rotor poles provided with concentrated DC excitation coils. The peripheral speeds are lower than those for turbogenerators, even for high-power hydrogenerators (for 200 MW 14 m rotor diameter at 75 rpm, and $2p_1 = 80$, $f_1 = 50$ Hz, the peripheral speed $U = \pi \times D_r \times n = \pi \times 14 \times 75/60 > 50$ m/sec). About 80 m/sec is the limit, in general, for salient pole rotors. Still, the excitation coils have to be protected against centrifugal forces.

The rotor pole shoes may be made of laminations, in order to reduce additional rotor losses, but the rotor pole bodies and core are made of mild magnetic solid steel.

With a large number of poles, the stator windings are built for a smaller number of slot/pole couplings: between 6 and 12, in many cases. The number of slots per pole and phase, q , is thus between two and four. The smaller the value of q , the larger the space harmonics present in the electromagnetic force. A fractionary q might be preferred, say 2.5, which also avoids the subharmonics and leads to a cleaner (more sinusoidal) electromagnetic force, to comply with the current standards.

The rotor pole shoes are provided with slots that house copper bars short-circuited by copper rings to form a rather complete squirrel cage. A stronger damper cage was thus obtained.

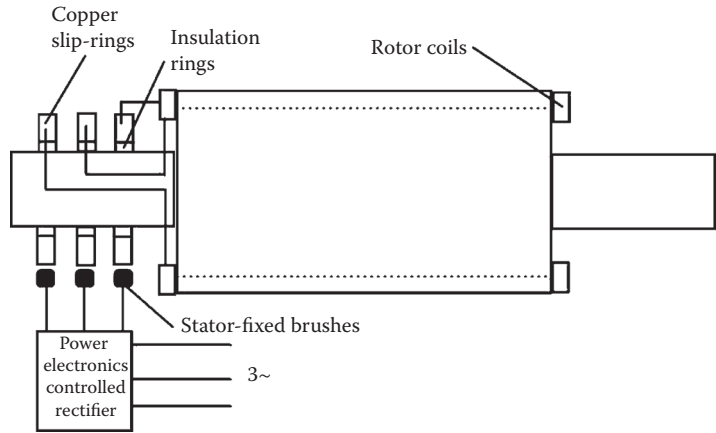


FIGURE 2.6 Slip-ring-brush power electronics rectifier DC excitation system.

DC excitation power on the rotor is transmitted by either:

- Copper slip-rings and brushes (Figure 2.6)
- Brushless excitation systems (Figure 2.7)

The controlled rectifier, with power around 3% of generator rated power, and with a sizable voltage reserve to force the current into the rotor quickly, controls the DC excitation currents according to the needs of generator voltage and frequency stability.

Alternatively, an inverted synchronous generator (with its three-phase AC windings and diode rectifier placed on the rotor and the DC excitation in the stator) may play the role of a brushless exciter (Figure 2.7). The field current of the exciter is controlled through a low-power half-controlled rectifier. Unfortunately, the electrical time constant of the exciter generator notably slows the response in the main synchronous generator excitation current control. Still another brushless exciter could be built around

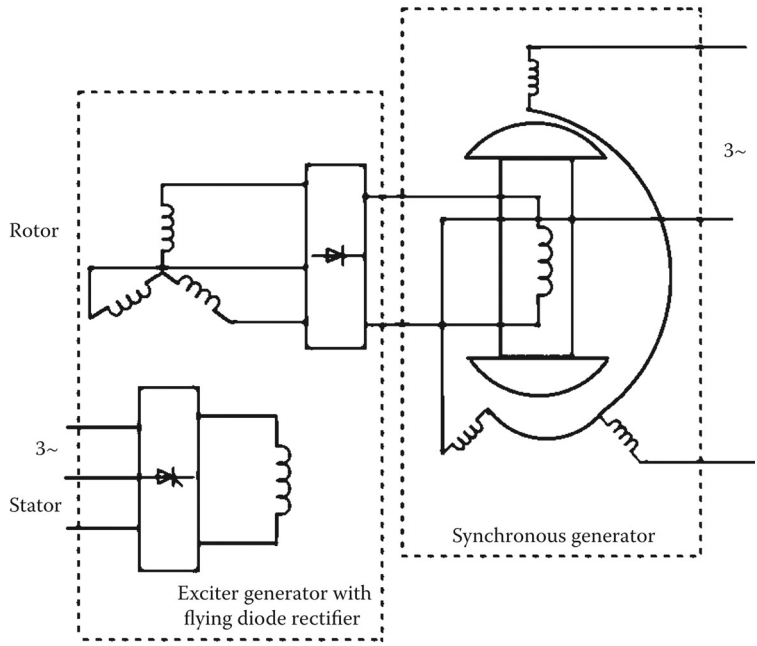


FIGURE 2.7 Brushless exciter with “flying diode” rectifier for synchronous generators.

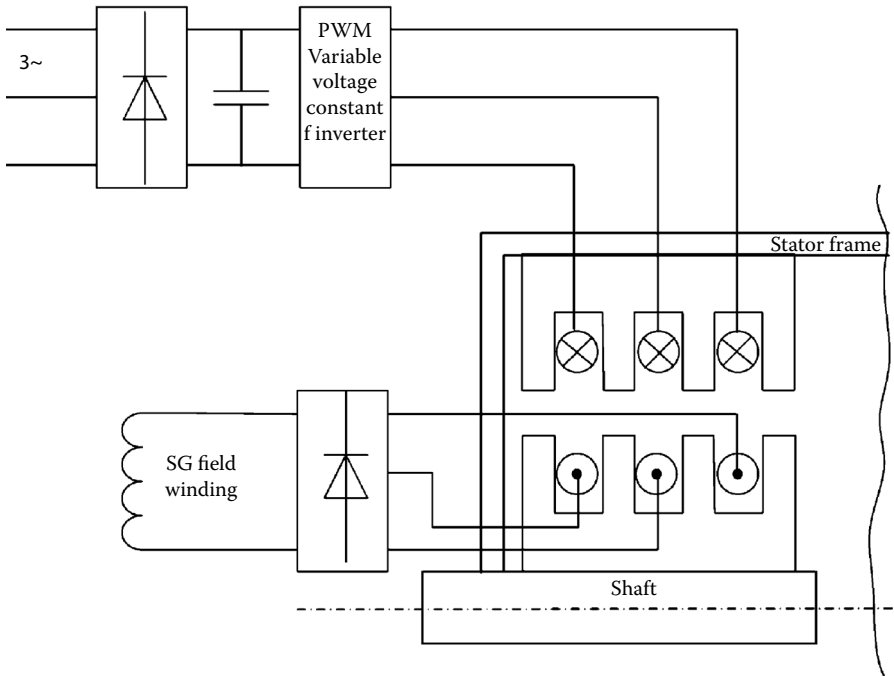


FIGURE 2.8 Rotating transformer with inverter in the rotor as brushless exciter.

a single-phase (or three-phase) rotating transformer working at a frequency above 300 Hz to cut its volume considerably (Figure 2.8). An inverter is required to feed the transformer, primarily at variable voltage but constant frequency. The response time in the generator's excitation current control is short, and the size of the rotating transformer is rather small. Also, the response in the excitation control does not depend on speed and may be used from a standstill.

Claw-pole (Lundell) synchronous generators are now built mainly for use as car alternators. The excitation winding power is reduced considerably for the multiple rotor construction ($2p_1 = 10, 12, 14$) to reduce external diameter and machine volume.

The claw-pole solid cast iron structure (Figure 2.9) is less costly to manufacture, while the single ring-shape excitation coil produces a multipolar airgap field (though with a three-dimensional field path) with reduced copper volume and DC power losses.

The stator holds a simplified three-phase single-layer winding with three slots per pole, in general. Though slip-rings and brushes are used, the power transmitted through them is small (in the order of 60 to 200 W for car and truck alternators); thus, low-power electronics are used to control the output. The total cost of the claw-pole generator for automobiles, including field current control and the diode full-power rectifier, is low, and so is the specific volume.

However the total efficiency, including the diode rectifier and excitation losses, is low at 14 V DC output: below 55%. To blame are the diode losses (at 14 V DC), the mechanical losses, and the eddy currents induced in the claw poles by the space and time harmonics of the stator currents magnetomotive force. Increasing the voltage to 42 V DC would reduce the diode losses in relative terms, while the building of the claw poles from composite magnetic materials would notably reduce the claw-pole eddy current losses. A notably higher efficiency would result, even if the excitation power might slightly increase, due to the lower permeability ($500 \mu_0$) of today's best composite magnetic materials. Also, higher power levels might be obtained.

The concept of a claw-pole alternator may be extended to the MW range, provided the number of poles is increased (at 50/60 Hz or more) in variable speed wind and microhydrogenerators with DC-controlled output voltage of a local DC bus.

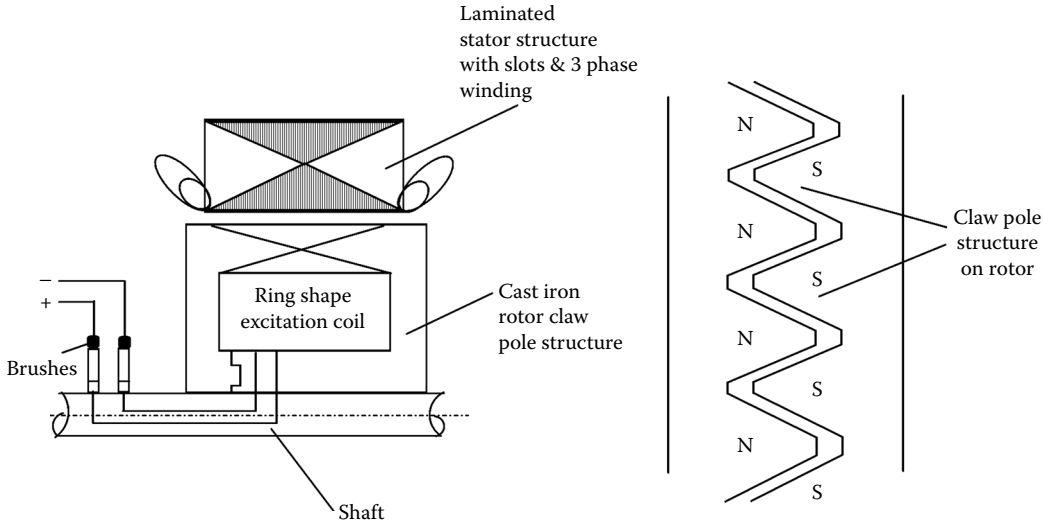


FIGURE 2.9 The claw-pole synchronous generator.

Though the claw-pole synchronous generator could be built with the excitation on the stator, to avoid brushes, the configuration is bulky, and the arrival of high-energy PMs for rotor DC excitation has put it apparently to rest.

2.3 Permanent Magnet Synchronous Generators

The rapid development of high-energy PMs with a rather linear demagnetization curve led to widespread use of PM synchronous motors for variable speed drives [6–10]. As electric machines are reversible by principle, the generator regime is available, and, for direct-driven wind generators in the hundreds of kilowatt or MW range, such solutions are being proposed. Super-high-speed gas-turbine-driven PM synchronous generators in the 100 kW range at 60 to 80 krpm are also introduced. Finally, PM synchronous generators are being considered as starter generators for the cars of the near future.

There are two main types of rotors for PM synchronous generators:

- With rotor surface PMs (Figure 2.10) — nonsalient pole rotor (SPM)
- With interior PMs (Figure 2.11a through Figure 2.11c) — salient pole rotor (IPM)

The configuration in Figure 2.10 shows a PM rotor made with parallelepipedic PM pieces such that each pole is patched with quite a few of them, circumferentially and axially.

The PMs are held tight to the solid (or laminated) rotor iron core by special adhesives, and a highly resilient resin coating is added for mechanical rigidity.

The stator contains a laminated core with uniform slots (in general) that house a three-phase winding with distributed (standard) coils or with concentrated (fractionary) coils.

The rotor is practically isotropic from the magnetic point of view. There is some minor difference between the d and the q axis magnetic permeances, because the PM recoil permeability ($\mu_{\text{rec}} = (1.04 - 1.07) \mu_0$ at 20°C) increases somewhat with temperature for NeFeB and SmCo high-energy PMs.

So, the rotor may be considered as magnetically nonsalient (the magnetization inductances L_{dm} and L_{qm} are almost equal to each other).

To protect the PMs, mechanically, and to produce reluctance torque, the interior PM pole rotors were introduced. Two typical configurations are shown in Figure 2.11a through Figure 2.11c.

Figure 2.11a shows a practical solution for two-pole interior PM (IPM) rotors. A practical $2p_1 = 4, 6, \dots$ IPM rotor as shown in Figure 2.11b has an inverse saliency: $L_{\text{dm}} < L_{\text{qm}}$, as is typical with IPM machines.

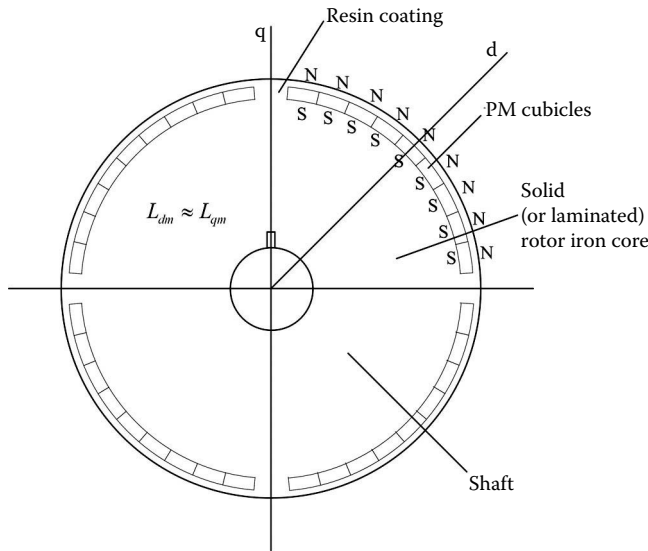


FIGURE 2.10 Surface PM rotor ($2p_1 = \text{four poles}$).

Finally, a high-saliency rotor ($L_{dm} > L_{qm}$), obtained with multiple flux barriers and PMs acting along axis q (rather than axis d), is presented in [Figure 2.11c](#). It is a typical IPM machine but with large magnetic saliency. In such a machine, the reluctance torque may be larger than the PM interactive torque. The PM field first saturates the rotor flux bridges and then overcompensates the stator-produced field in axis q . This way, the stator flux along the q axis decreases with current in axis q . For flux weakening, the I_d current component is reduced. A wide constant power (flux weakening) speed range of more than 5:1 was obtained this way. Starters/generators on cars are a typical application for this rotor.

As the PM's role is limited, lower-grade (lower B_r) PMs, at lower costs, may be used.

It is also possible to use the variable reluctance rotor with high magnetic saliency ([Figure 2.11a](#)) without permanent magnets. With the reluctance generator, either power grid or stand-alone mode operation is feasible. For stand-alone operation, capacitor self-excitation is needed. The performance is moderate, but the rotor cost is also moderate. Standby power sources would be a good application for reluctance synchronous generators with high saliency $L_{dm}/L_{qm} > 4$.

PM synchronous generators are characterized by high torque (power) density and high efficiency (excitation losses are zero). However, the costs of high-energy PMs are still up to \$100 per kilogram. Also, to control the output, full-power electronics are needed in the stator ([Figure 2.12](#)).

A bidirectional power flow pulse-width modulator (PWM) converter, with adequate filtering and control, may run the PM machine either as a motor (for starting the gas turbine) or as a generator, with controlled output at variable speed. The generator may work in the power-grid mode or in stand-alone mode. These flexibility features, together with fast power-active and power-reactive decoupled control at variable speed, may make such solutions a way of the future, at least in the tens and hundreds of kilowatts range.

Many other PM synchronous generator configurations were introduced, such as those with axial airgap. Among them, we will mention one that is typical in the sense that it uses the IPM reluctance rotor ([Figure 2.11c](#)), but it adds an electrical excitation. ([Figure 2.13](#)) [11].

In addition to the reluctance and PM interaction torque, there will be an excitation interaction torque. The excitation current may be positive or negative to add or subtract from I_d current component in the stator. This way, at low speeds, the controlled positive field current will increase and control the output voltage, while at high speeds, a negative field current will suppress the electromagnetic torque, when needed, to keep the voltage constant.

For DC-controlled output only a diode rectifier is necessary, as the output voltage is regulated via DC current control in four quadrants. A low-power four-quadrant chopper is needed. For wide speed

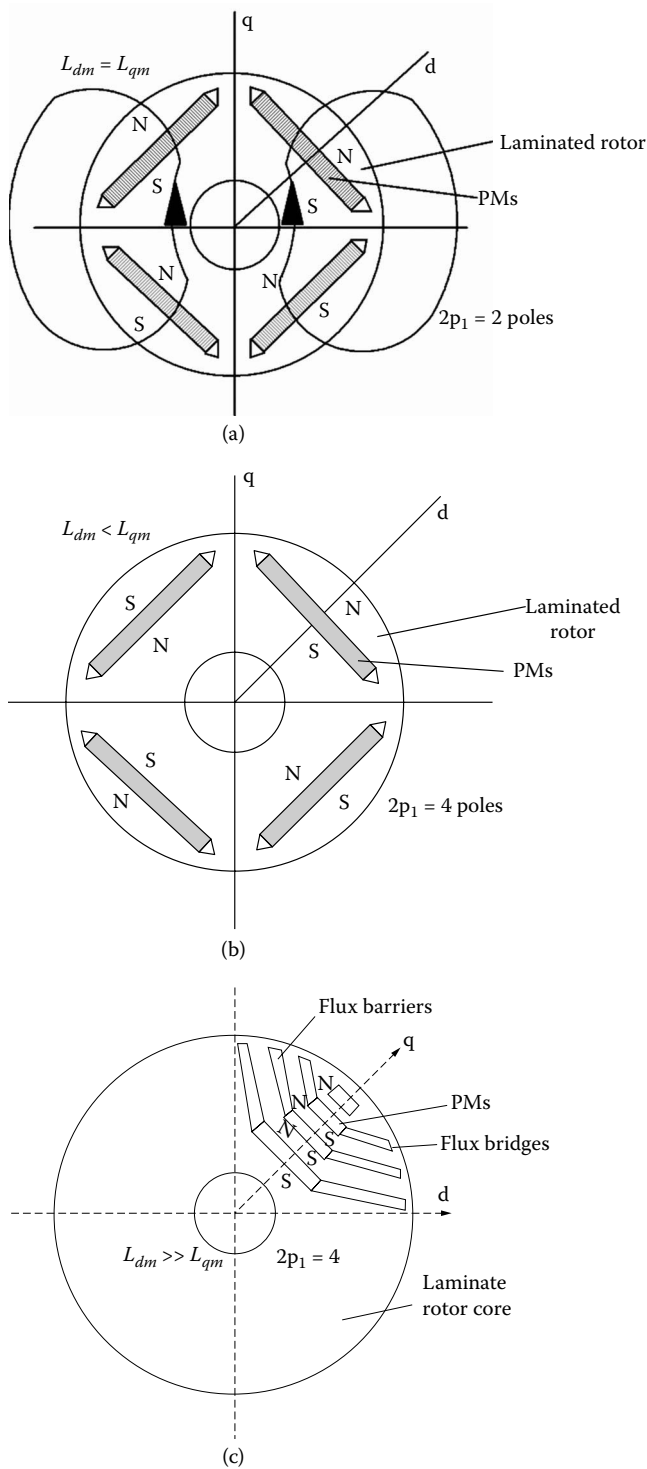


FIGURE 2.11 Interior PM rotors: (a) $2p_1 = 2$ poles, (b) $2p_1 = 4$, and (c) with rotor flux barriers (IPM – reluctance).

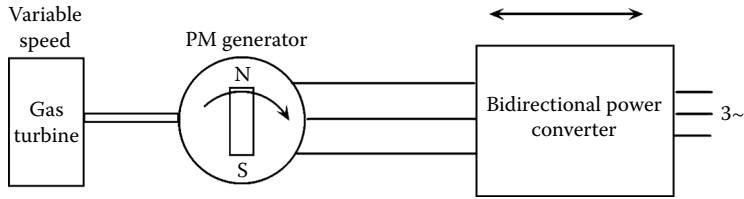


FIGURE 2.12 Bidirectional full-power electronics control.

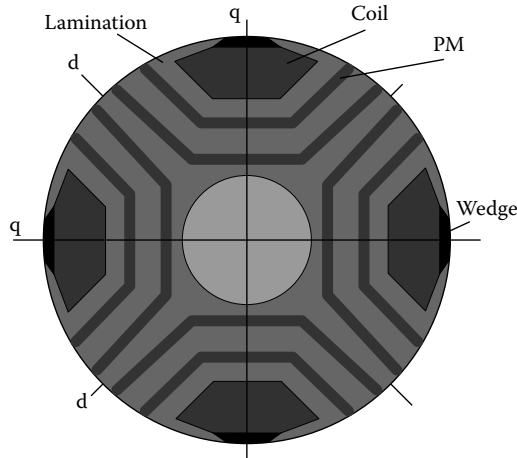


FIGURE 2.13 Biaxial excitation PM reluctance rotor generator (biaxial excitation generator for automobiles [BEGA]).

range applications such a hybrid excitation rotor may be a competitive solution. The rotor is not very rugged mechanically, but it can easily handle peripheral speeds of up to 50 m/sec (10,000 rpm for 0.1 m diameter rotor).

2.4 The Homopolar Synchronous Generator

Placing both the DC excitation coils and the three-phase AC winding on the stator characterizes the so-called homopolar (or inductor) synchronous machine (generator and motor; see Figure 2.14a through Figure 2.14c).

The rather rugged rotor with solid (even laminated) salient poles and solid core is an added advantage. The salient rotor poles (segments) and interpoles produce a salient magnetic structure with a notable saliency ratio, especially if the airgap is small.

Consequently, the magnetic field produced by the DC field current closes paths, partially axially and partially circumferentially, through stator and rotor, but it is tied (fixed) to the rotor pole axis.

It is always maximum in the axis of rotor poles and small, but of the same polarity, in the axis of interpoles. An AC airgap magnetic component is present in this homopolar distribution. Its peak value is ideally 50% of maximum airgap field of the DC excitation current. Fringing reduces it 35 to 40% (Figure 2.14a through Figure 2.14c), at best.

The machine is a salient pole machine with doubled airgap, but it behaves as a nonsalient pole rotor one and with rotor excitation.

So, for the same airgap flux density fundamental B_{g1} (Figure 2.14a through Figure 2.14c), the same mechanical airgap, the DC magnetomotive force of the field winding is doubled, and the power loss quadruples. However, the ring-shaped coil reduces the copper weight and losses (especially when the

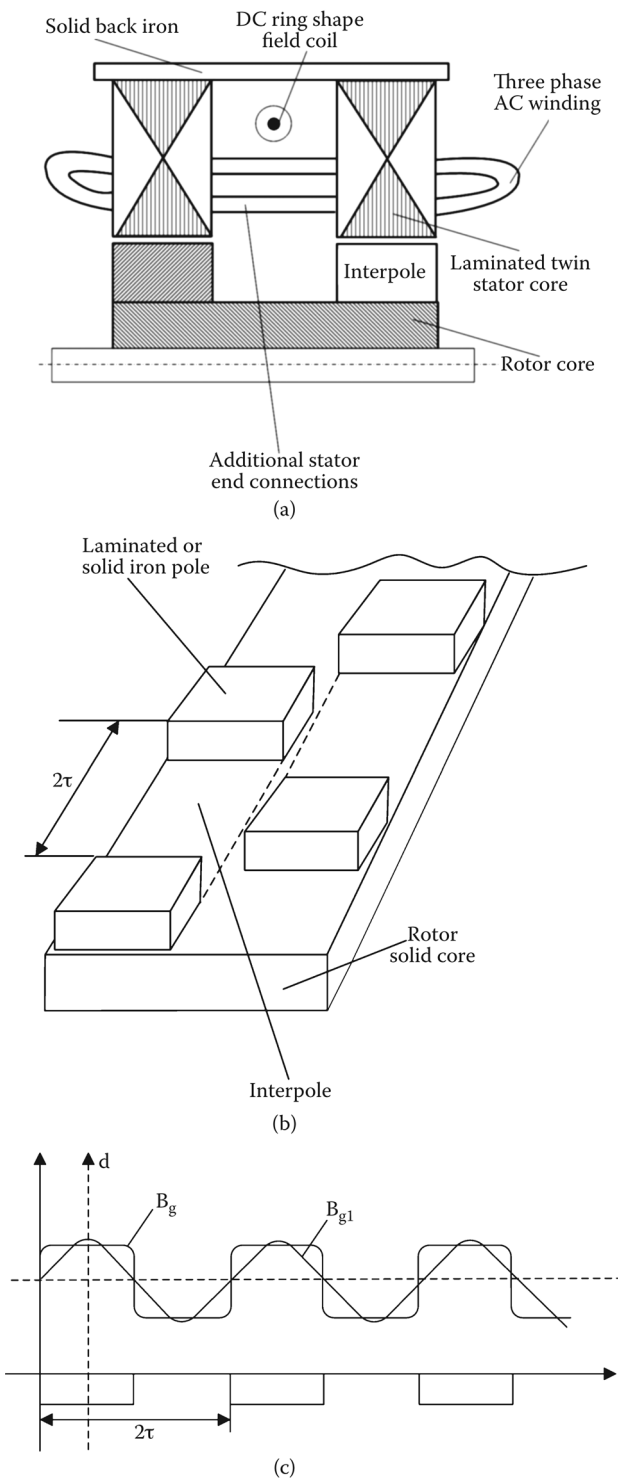


FIGURE 2.14 The homopolar synchronous generator: (a) and (b) the geometry and (c) airgap excitation field distribution.

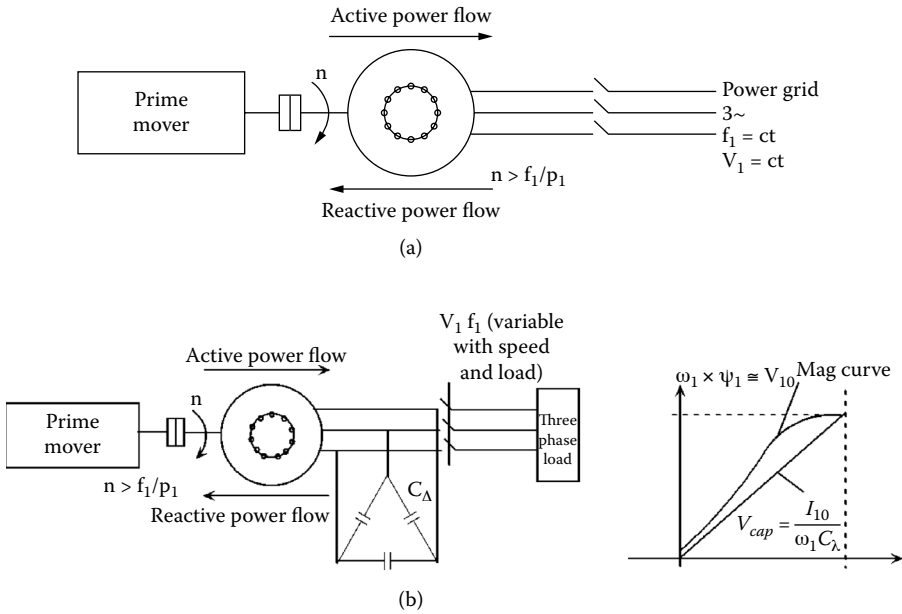


FIGURE 2.15 Cage-rotor induction generator: (a) at power grid: $V_1 = ct$, $f_1 = ct$, and (b) stand-alone (capacitor excited): V_1, f_1 , variable with speed and load.

number of poles increases) in comparison with a multipolar heteropolar DC rotor excitation system. The blessing of circularity comes into place here. We also have to note the additional end connection in the middle of the stator AC three-phase winding, between the two slotted laminated cores.

The rotor mechanical ruggedness is superior only with solid iron poles when made in one piece. Unfortunately, stator magnetomotive force and slot space harmonics induce eddy currents in the rotor solid poles, notably reducing the efficiency, typically below 90% in a 15 kW, 15,000 rpm machine.

2.5 Induction Generator

The cage-rotor induction machine is known to work as a generator, provided the following:

- The frequency f_1 is smaller than $n \times p_1$ (speed $\times$ pole pairs): $S < 0$ (Figure 2.15a).
- There is a source to magnetize the machine.

An induction machine working as a motor, supplied to fixed frequency and voltage f_1, V_1 power grid becomes a generator if it is driven by a prime mover above no load ideal speed f_1/p_1 :

$$n > \frac{f_1}{p_1} \quad (2.5)$$

Alternatively, the induction machine with the cage rotor may self-excite on a capacitor at its terminals (Figure 2.15b).

For an IG connected to a strong (constant frequency and voltage) power grid, when the speed n increases (above f_1/p_1), the active power delivered to the power grid increases, but so does the reactive power drawn from the power grid.

Many existing wind generators use such cage-rotor IGs connected to the power grid. The control is only mechanical. The blade pitch angle is adjusted according to wind speed and power delivery requirements. However, such IGs tend to be rigid, as they are stable only until n reaches the following value:

$$n_{\max} = \frac{f_1}{p_1} (1 + |S_K|) \quad (2.6)$$

where S_K is the critical sleep, which decreases with power and is, anyway, below 0.08 for IGs in the hundreds of kilowatts. Additional parallel capacitors at the power grid are required to compensate for the reactive power drained by the IG.

Alternatively, the reactive power may be provided by parallel (plus series) capacitors (Figure 2.15b). In this case, we have a self-excitation process that requires some remanent flux in the rotor (from previous operation) and the presence of magnetic saturation (Figure 2.15b). The frequency f_1 of self-excitation voltage (under no load) depends on the capacitor value and on the magnetization curve of the induction machine $\Psi_1(I_{10})$:

$$V_{10} \approx \Psi_1(I_{10}) \cdot 2 \cdot \pi \cdot f_1 \approx V_{C_Y} = I_{10} \frac{3}{C_{\Delta} \cdot 2 \cdot \pi \cdot f_1} \quad (2.7)$$

The trouble is that on load, even if the speed is constant through prime mover speed control, the output voltage and frequency vary with load. For constant speed, if frequency reduction under a load of 1 Hz is acceptable, voltage control suffices. A three-phase AC chopper (Variac™) supplying the capacitors would do it, but the harmonics introduced by it have to be filtered out. In simple applications, a combination of parallel and series capacitors would provide constant (with 3 to 5% regulation) voltage up to rated load.

Now, if variable speed is to be used, then, for constant voltage and frequency, PWM converters are needed. Such configurations are illustrated in Figure 2.16a and Figure 2.16b. A bidirectional power flow PWM converter (Figure 2.16a) provides both generating and motoring functions at variable speed. The capacitor in the DC line of the converter may lead not only to active, but also to reactive, power delivery. Connection to the power grid without large transients is implicit, and so is fast, decoupled, active, and reactive power control.

The stand-alone configuration in Figure 2.16b is less expensive, but it provides only unidirectional power flow. A typical V_1/f_1 converter for drives is used. It is possible to inverse the connections, that is, to connect the diode rectifier and capacitors to the grid and the converter to the machine. This way, the system works as a variable speed drive for pumping and so forth, if a local power grid is available. This commutation may be done automatically, but it would take 1 to 2 min. For variable speed, in a limited range, an excitation capacitor in two stages would provide the diode rectifier with only slightly variable DC link voltage. Provided the minimum and maximum converter voltage limits are met, the former would operate over the entire speed range. Now, the converter is V_1/f_1 controlled for constant voltage and frequency.

A transformer (Y, Y_0) may be needed to accommodate unbalanced (or single-phase) loads.

The output voltage may be close-loop controlled through the PWM converter. On the other end, the bidirectional PWM converter configuration may be provided with a reconfigurable control system so as to work not only on the power grid, but also to separate itself smoothly to operate as a stand-alone or to wait on standby and then be reconnected smoothly to the power grid. Thus, multifunctional power generation at variable speed is produced. As evident in Figure 2.16a and Figure 2.16b, full-power electronics are required. For a limited speed range, say up to 25%, it is possible to use two IGs with cage-rotor and different pole numbers ($2p_2/2p_1 = 8/6, 5/4, 4/3, \dots$). The one with more poles ($2p_2 > 2p_1$) is rated at 25% of rated power and is fed from a bidirectional power converter sized also at about 25%. The scheme works at the power grid (Figure 2.17).

The soft-starter reduces the synchronization transients and disconnects the 100% IG when the power required is below 25%. Then, the 25% IG remains alone at work, at variable speed ($n < f_1/p_1$), to tap the energy available from (for example) low-speed wind or from a low-head microhydroturbine. Also, above 25% load, when the main (100%) IG works, the 25% IG may add power as generator or work in motoring

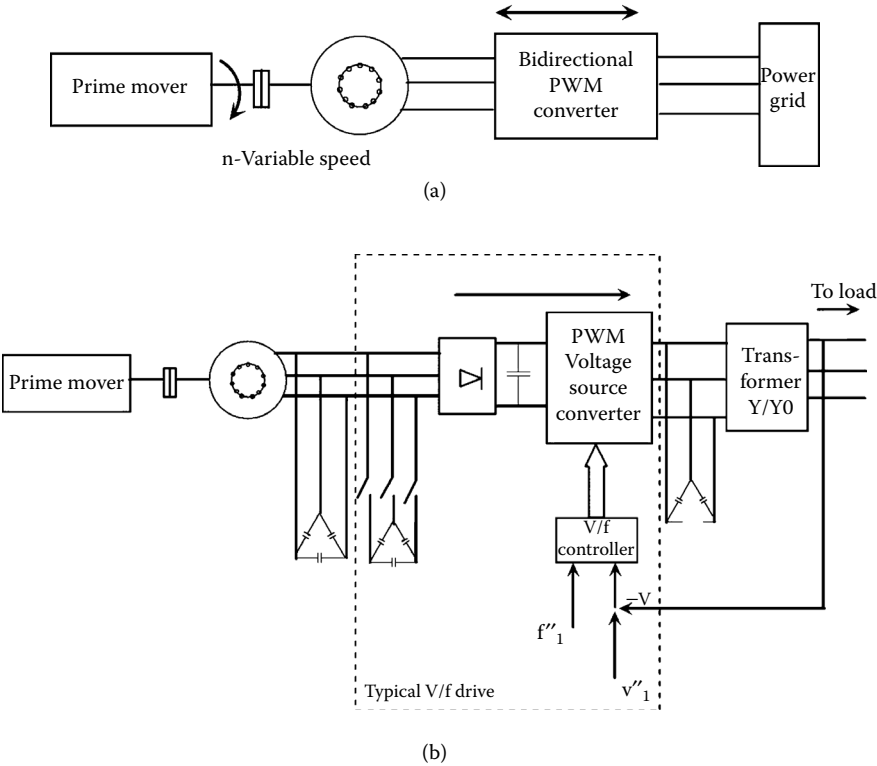


FIGURE 2.16 Cage-rotor induction generators for variable speed: (a) at power grid $V_1 = ct., f_1 = ct.$, and (b) stand-alone $V_1'' = ct., f_1'' = ct.$ (controlled).

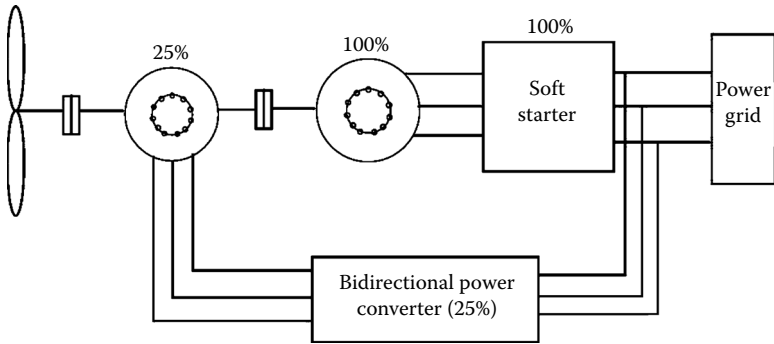


FIGURE 2.17 Dual-induction generator system for limited speed variation range.

for better dynamics and stability. Now, we may imagine a single rotor-stator IG with two separate stator windings ($2p_2 > 2p_1$) to perform the same task.

The reduction in rating, from 100% to 25%, of the bidirectional PWM converter is noteworthy.

The main advantage of the dual IG or dual-stator winding IG is lower cost, although the cost is for lower performance (low-speed range above f_1/p_1).

2.6 The Wound Rotor (Doubly Fed) Induction Generator (WRIG)

It all started between 1907 and 1913, with the Scherbius and Kraemer cascade configurations, which are both slip-power recovery schemes of wound-rotor induction machines. Leonhard analyzed it pertinently

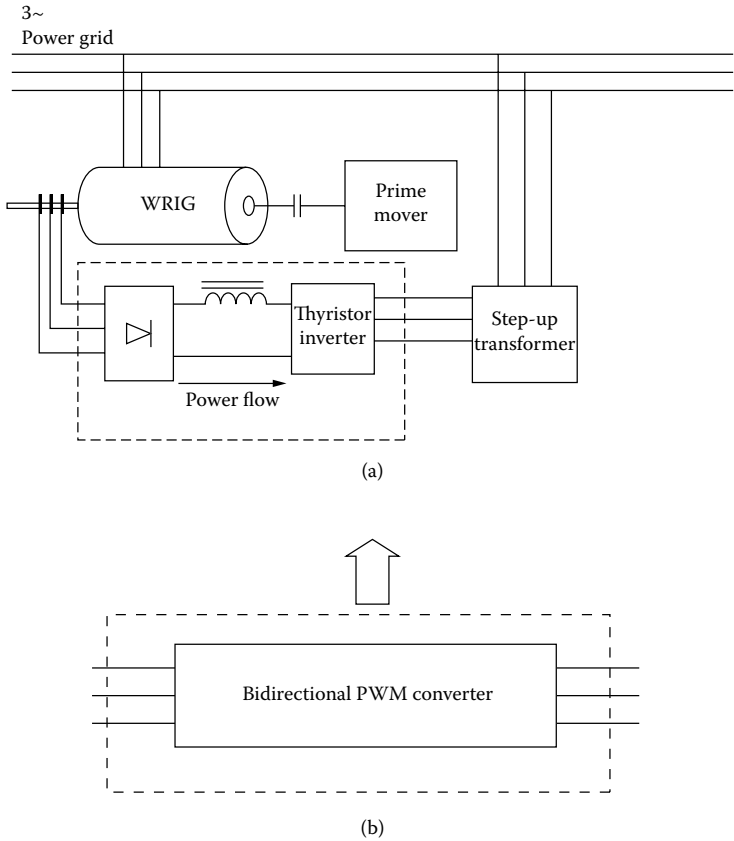


FIGURE 2.18 Wound rotor induction generator (WRIG): (a) with diode rectifier (slip recovery system), and (b) with bidirectional pulse-width modulator (PWM) converter.

in 1928, but adequate power electronics for it were not available by then. A slip recovery scheme with thyristor power electronics is shown in Figure 2.18a. Unidirectional power flow, from IG rotor to the converter, is only feasible because of the diode rectifier. A step-up transformer is necessary for voltage adaption, while the thyristor inverter produces constant voltage and frequency output. The principle of operation is based on the frequency theorem of traveling fields.

$$f_1 = np_1 + f_2; f_2 < 0, \text{ and variable } f_1 = ct \tag{2.8}$$

Negative frequency means that the sequence of rotor phases is different from the sequence of stator phases. Now if f_2 is variable, n may also be variable, as long as Equation 2.8 is fulfilled.

That is, constant frequency f_1 is provided in the stator for adjustable speed. The system may work at the power grid or even as a stand-alone, although with reconfigurable control. When $f_2 > 0, n < f_1/p_1$, we have subsynchronous operation. The case for $f_2 < 0, n > f_1/p_1$ corresponds to hypersynchronous operation. Synchronous operation takes place at $f_2 = 0$, which is not feasible with the diode rectifier current source inverter, but it is feasible with the bidirectional PWM converter.

The slip recovery system can work as a subsynchronous ($n < f_1/p$) motor or as a supersynchronous ($n > f_1/p$) generator. The WRIG with bidirectional PWM converter may work as a motor and generator for both subsynchronous and supersynchronous speed. The power flow directions for such a system are shown in Figure 2.19a and Figure 2.19b.

The converter rating is commensurable to speed range, that is, to maximum slip $S_{\max}$:

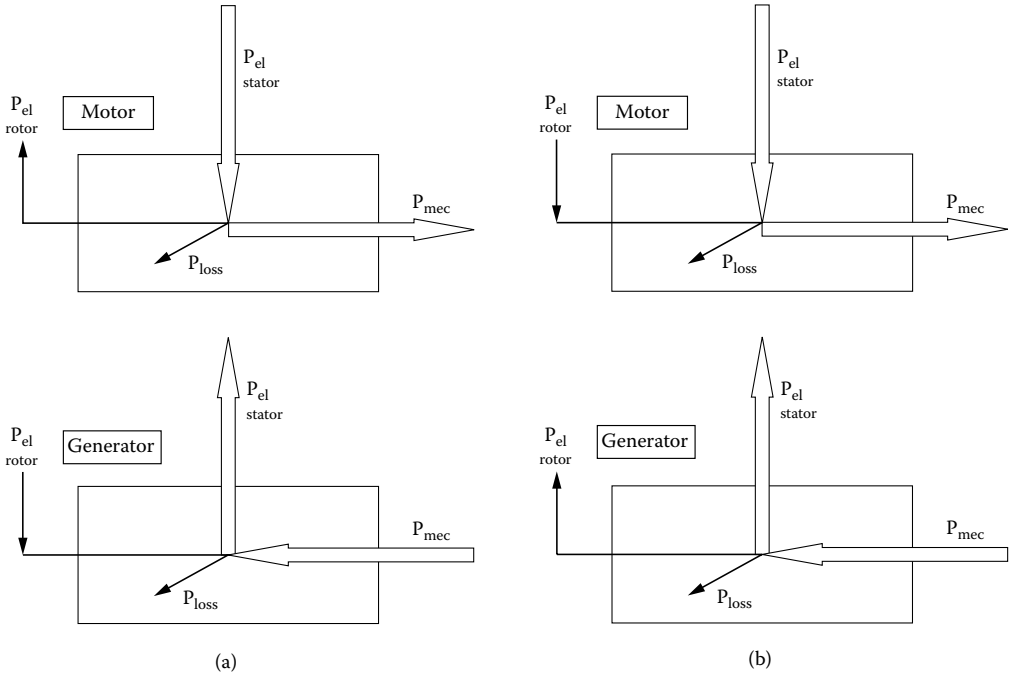


FIGURE 2.19 Operation modes of wound rotor induction generator (WRIG) with bidirectional pulse-width modulator (PWM) converter (in the rotor): (a) $S < 0$ and (b) $S > 0$.

$$KVA_{rating} = K \frac{f_{2max}}{f_1} \times 100 [\%] \quad (2.9)$$

$K = 1$ – 1.4 depending on the reactive power requirements from the converter

Notice that, being placed in the rotor circuit, through slip-rings and brushes, the converter rating is around $|S_{max}|$ in percent. The larger the speed range, the larger the rating and the costs of the converter. Also, the fully bidirectional PWM converter — as a back-to-back voltage source multilevel PWM converter system — may provide fast and continuous decoupled active and reactive power control operation, even at synchronism ($f_2 = 0$, DC rotor excitation). And, it may perform the self-starting as well. The self-starting is done by short-circuiting the stator, previously disconnected from the power grid, and supplying the rotor through the PWM converter in the subsynchronous motoring mode. The rotor accelerates up to a prescribed speed corresponding to $f_2 > f_1(1 - S_{max})$. Then, the stator winding is opened and, with the rotor freewheeling, the stator no load voltage, sequence and frequency are adjusted to coincide with that of the power grid, by adequate PWM converter control. Finally, the stator winding is connected to the power grid without notable transients.

This kind of rotor-starting procedure requires $f_2 \approx (0.8 - 1)f_1$, which means that the standard cyclo-converter is out of the question. So, it is only the back-to-back voltage PWM multilevel converter or the matrix converter that is suitable for full exploitation of motoring/generating at sub- and supersynchronous speeds, so typical in pump storage applications.

2.7 Parametric Generators

Parametric generators exploit the magnetic anisotropy of both stator and rotor. PMs may be added on the stator or on the rotor. Single magnetic saliency with PMs on the rotor is also used in some configurations. Parametric generators use nonoverlapping (concentrated) windings to reduce end-connection

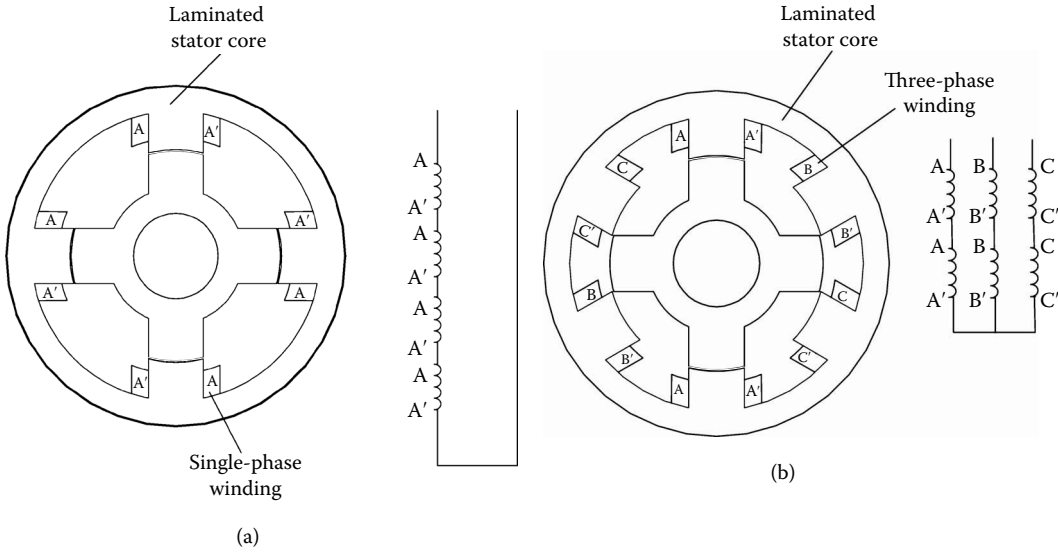


FIGURE 2.20 Switched reluctance generators (SRGs): (a) single-phase: 4/4 (4×4 poles) and (b) three-phase: 6/4 (6×4 poles).

copper losses on the stator. As the stator magnetomotive force does not produce a pure traveling field, there are core losses both in the stator and in the rotor. The simplicity and ruggedness of such generators make them adequate for use in some applications.

Among parametric generators, some of the most representative are detailed here:

- The switched reluctance generators (SRGs):
 - Without PMs
 - With PMs on the stator or on the rotor
- The transverse flux generators (TFGs):
 - With rotor PMs
 - With stator PMs
- The flux reversal generators (FRGs):
 - With PMs on the stator
 - With PMs on the rotor (and flux concentration)
- The linear motion alternators (LMAs):
 - With coil mover and PMs on the stator
 - With PM mover, tubular or flat (with PM flux concentration)
 - With iron mover and PMs on the stator

The SRG [12] has a double saliency magnetic laminated structure — on the stator and rotor — and concentrated coils on the stator (Figure 2.20a and Figure 2.20b). The stator phases are PWM voltage fed as long as the rotor poles are approaching them, one at a time, for the three-phase configuration. The phase inductances vary with rotor position (Figure 2.21a and Figure 2.21b) and, at least for the three-phase configuration, there is little magnetic coupling between phases.

Eventually, each phase is turned on around point A (in Figure 2.21a and Figure 2.21b); then it magnetizes the phase, and the $dL/d\theta$ effect produces a motion-induced voltage (electromagnetic force) which, in interaction with the phase current, produces torque. The phase is turned off around point B, when the next phase is turned on. The current polarity is not relevant; thus, positive current is flowed through voltage PWM. The maximum voltage is applied until the phase current magnetizes to maximum admitted current.

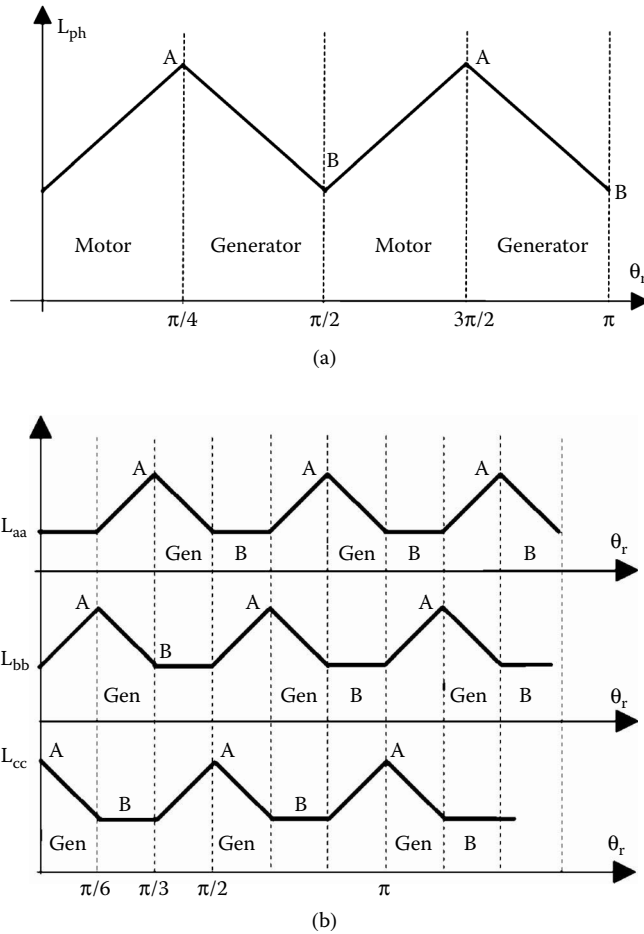


FIGURE 2.21 Phase inductance vs. rotor position: (a) the single-phase 4/4 switched reluctance generator (SRG) and (b) the three-phase 6/4 SRG.

As part of the AB interval available for generating is lost to the magnetization process, the latter takes up around 30% of energy available per cycle. For the single-phase machine, the torque, as expected, has notches, as only the negative slopes of the inductance are adequate for generating.

It is machine simplicity and ruggedness that characterize SRGs. High speed is feasible. Rotor higher temperature due to the local environment is also acceptable, because there are no PMs or windings on the rotor. PMs may be added on the rotor (Figure 2.22a and Figure 2.22b) [13,14]. In this situation, the current polarity has to change, and the torque production relies heavily on phase interaction through PMs. The reluctance torque is small.

Alternatively, PMs may be placed on the stator (Figure 2.22c) [15] with some PM flux concentration. Again, the reluctance torque is reduced, and PM torque prevails. The PM flux polarity in one phase does not change sign, so we may call it a homopolar PM excitation.

Other SRG configurations with homopolar excitation flux were proposed but did not reach very far in the markets.

2.7.1 The Flux Reversal Generators

In these configurations, reliance is on PM flux switch (reversal) in the stator-concentrated coils (Figure 2.23a [16]). The PM flux linkage in the stator coils of Figure 2.23a changes sign when the rotor moves

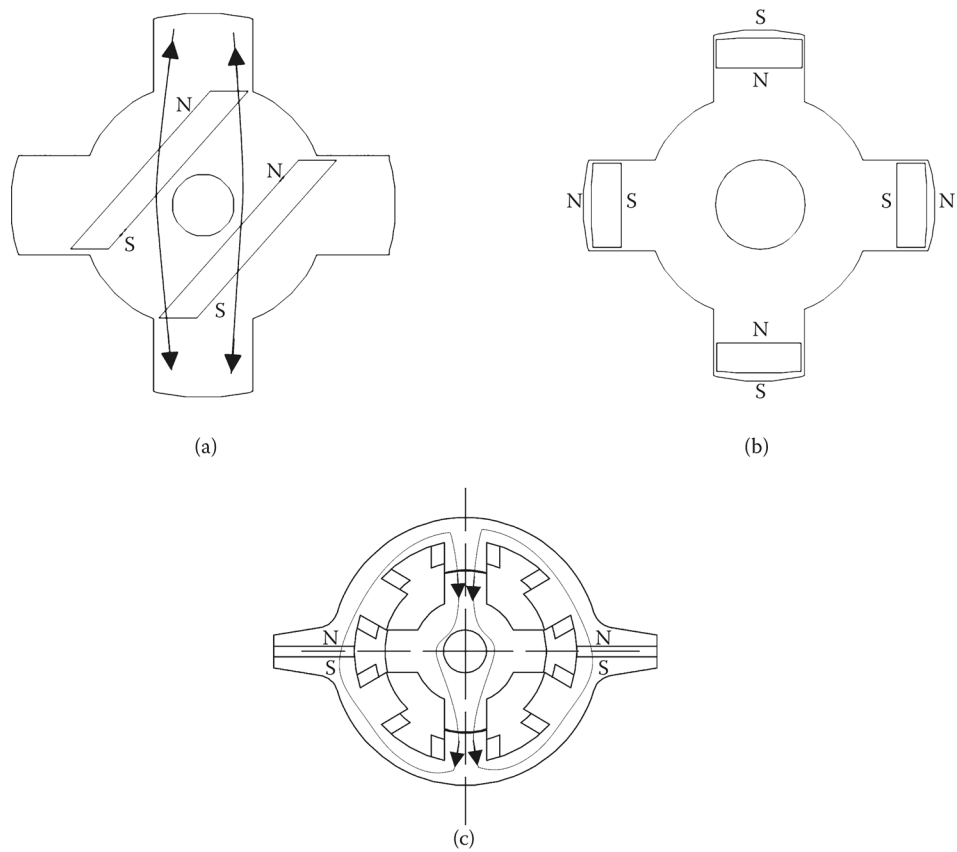


FIGURE 2.22 Permanent magnet (PM)-assisted switched reluctance generators (SRGs): (a) with long PMs on the rotor, (b) with short PMs on the rotor, and (c) with PMs on the stator.

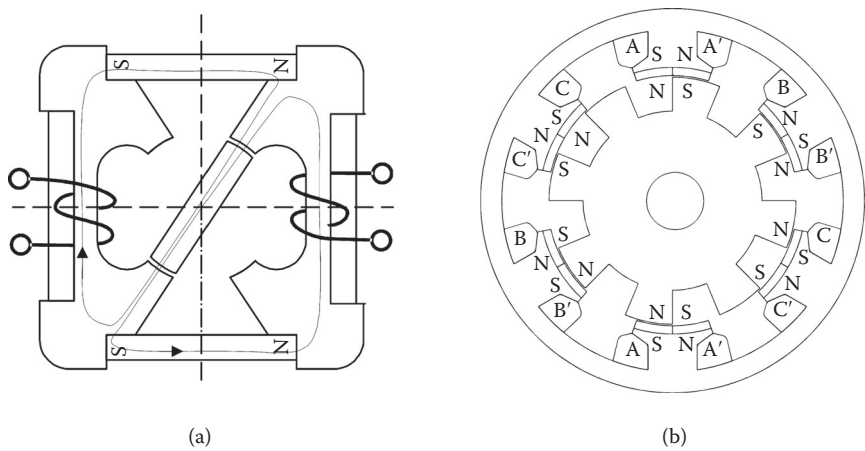


FIGURE 2.23 Flux reversal generators (FRGs) with stator permanent magnets (PMs): (a) the single-phase 4/2 flux-switch alternator and (b) the three-phase 6/8 FRG.

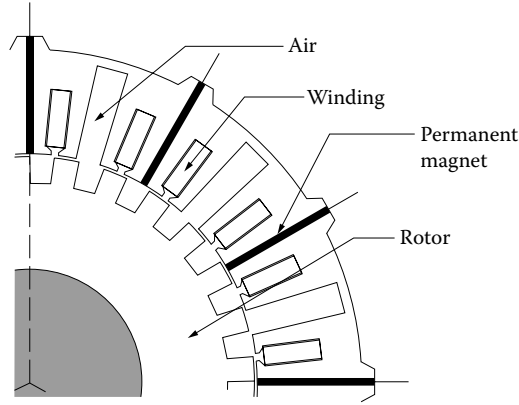


FIGURE 2.24 Three-phase flux reversal generator (FRG) with stator permanent magnet (PM) flux concentration.

90° (mechanical) and does the same, for each phase in [Figure 2.23b](#) for the three-phase FRG, when the rotor moves 22.5° mechanical degrees.

In general, it is π/N_r (which corresponds to electrical radius). The electrical and mechanical radians are related as follows:

$$\alpha_{el} = N_r \alpha_{mec}, f_1 = N_r \cdot n \quad (2.10)$$

So, the frequency of the electromagnetic force f_1 is as if the number of pole pairs on the rotor was N_r .

The three-phase FRG configuration [17] makes better use of the stator and rotor core, and the manufacturing process is easier than that for the single-phase configuration, as the coils are inserted by conventional technology. Premade stator poles, with coils on, may be mounted inside the stator back iron, as done with rotor poles in salient poles in hydrogenerators. The main problem is the large flux fringing due to the juxtaposition of the North and South Poles (there could be 2,4,6,... of them on a stator pole). This reduces the useful flux to about 0.3 to 0.4 of its ideal value (in homopolar stator excitation, this is normal). PM flux concentration should provide better torque density for the same power factor. A three-phase configuration as described is shown on [Figure 2.24](#).

It is evident that the manufacturing of a stator is a bit more complicated, and usage of the stator core is partial but still, PM flux concentration may increase the torque density without compromising the power factor too much. The phases are magnetically independent, and thus, high fault tolerance is expected.

For a better core utilization, the PMs with flux concentration may be placed on the rotor. An interior stator is added to complete the magnetic circuit ([Figure 2.25](#)).

The second (interior) windingless stator poses some manufacturing problems (the rotor also), but the higher torque/volume at an acceptable power factor may justify it. The power factor is mentioned here because it influences the converter kilo volt amps (KVAs) through reactive power demands.

FRGs are, in general, meant for mainly very low-speed applications, such as direct-driven wind generators on vessel generator/motors, and so forth.

2.7.2 The Transverse Flux Generators (TFGs)

TFGs are built in single-phase configurations with ring-shaped stator coils and surface PMs on the rotor ([Figure 2.26](#)) or with PM rotor flux concentration ([Figure 2.27](#)) [17,18].

The double-sided (dual-stator) configuration in [Figure 2.27](#) takes advantage of PM flux concentration on the rotor. In general, TFGs are characterized by moderately low winding losses, due to the blessing of the ring-shaped coil.

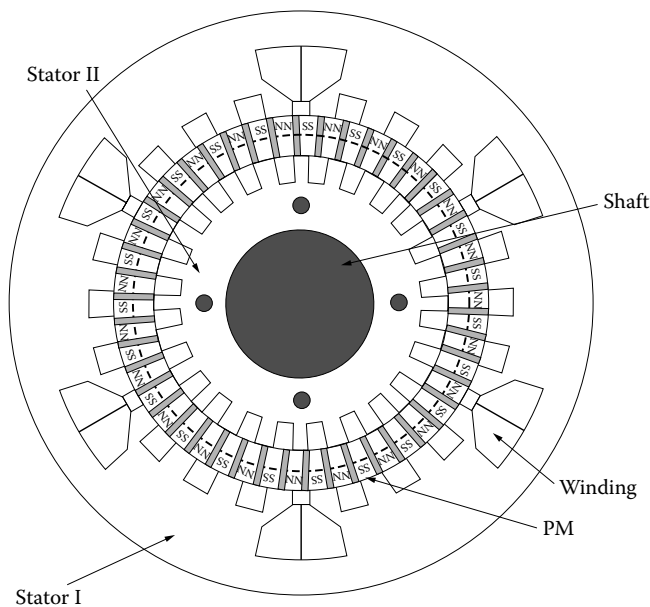


FIGURE 2.25 Flux reversal generator (FRG) with rotor permanent magnet (PM) flux concentration.

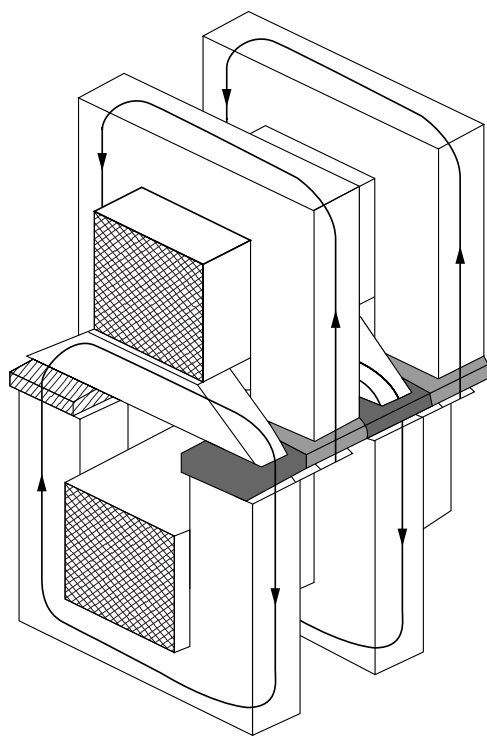


FIGURE 2.26 Double-sided transverse flux generator (TFG) with surface PM rotor.

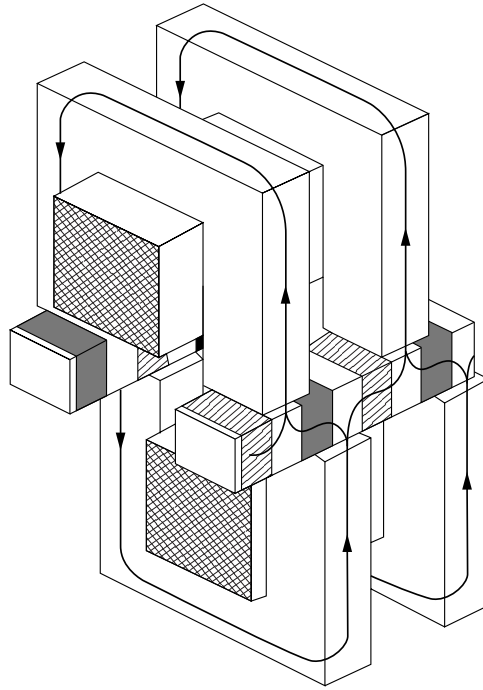


FIGURE 2.27 Double-sided transverse flux generator (TFG) with rotor PM flux concentration.

A three-phase machine is built by adding axially three single-phase units, properly displaced tangentially by $2/3$ of a pole with each other. It is evident that the stators could best be built from magnetic composite materials. However, this solution would reduce torque density, because the permeability of such materials is below $500 \mu_0$ under some magnetic saturation. The core losses would be reduced if frequency goes above 600 Hz with magnetic composite materials (magnetic powder).

The stator-PM TFG (originally called the axial flux circumferential current PM machine [AFCC] [19]) imposes the use of composite magnetic materials both on the stator and on the rotor due to its intricate geometry. Again, it is essentially a single-phase machine. PM flux concentration occurs along the axial direction. Good usage of PMs and cores is inherent in the axial-airgap stator PM FRG shown in [Figure 2.28a](#) and [Figure 2.28b](#).

FRGs need more PMs than usual, but the torque density is rather good, and compact geometries are very likely. The large number of poles on the rotor in most TFGs leads to a good frequency, unless speed is not very low.

The rather high torque density (in Nm/m^3 , or $[6 \text{ to } 9] \text{ N}/\text{cm}^2$ of rotor shear stress) is inherent, as the number of PM flux reversals (poles) in the stator ring-shaped coils is large per one revolution. This effect may be called torque magnification [11].

2.7.3 Linear Motion Alternators

The microphone is the classical example of a linear motion alternator (LMA) with moving coil. The loudspeaker illustrates its motoring operation mode.

Though there are many potential LMA configurations (or actuators), they all use PMs and fall into three main categories [20]:

- With moving coil (and stator PMs) — [Figure 2.29a](#)
- With moving PMs (and stator coil) — [Figure 2.29b](#)
- With moving iron (and stator PMs) — [Figure 2.29c](#)

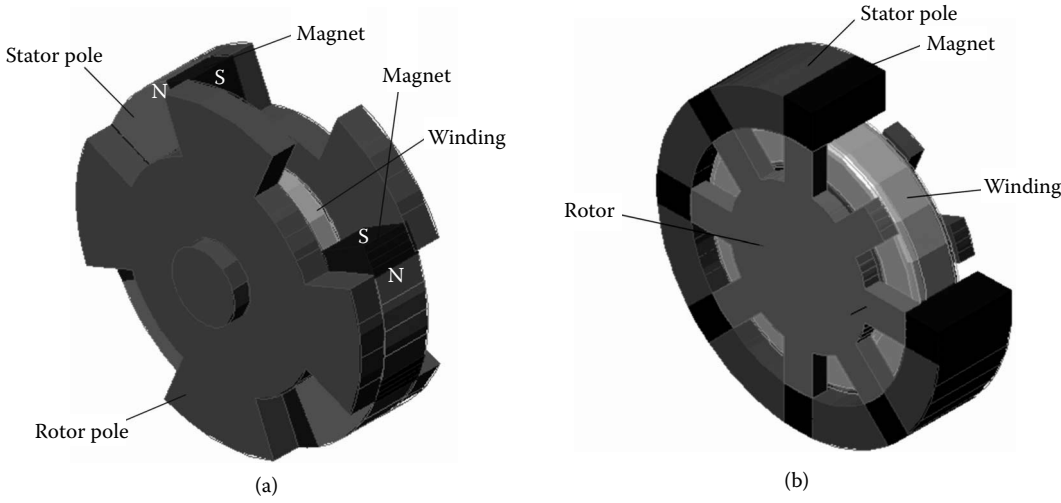


FIGURE 2.28 TFG with stator — permanent magnet (PM) flux concentration: (a) with axial airgap and (b) with radial airgap.

In essence, the PM flux linkage in the coil changes sign when the mover travels the excursion length l_{stroke} which serves as a kind of pole pitch. So they are, in a way, single-phase flux reversal machines. The average speed U_{av} is as follows:

$$U_{av} = 2 \cdot l_{stroke} \cdot f_1 \tag{2.11}$$

where f_1 = the frequency of mechanical oscillations.

To secure high efficiency, beryllium-copper flexured springs (Figure 2.30) are used to store the kinetic energy of the mover at excursion ends. They also serve as linear bearings. The proper frequency of these mechanical springs f_m should be equal to electrical frequency:

$$f_e = f_m = \frac{1}{2\pi} \sqrt{\frac{K}{m}} \tag{2.12}$$

where

- K = spring rigidity coefficient
- m = moving mass

The current is in phase with speed for best operation.

The strokes involved in LMAs are in the order of 0.5 to 100 mm or so. Their power, in general, is limited to 10 to 50 kW at 50 (60) Hz.

They are basically synchronous single-phase machines with harmonic motion and linear flux to position ideal variation.

Further increasing the power and volume requires — if average speed U_s is limited — configurations with PM flux concentration and three phases. Such a single-phase flat configuration, with moving PMs, is shown in Figure 2.31 [26].

Again, it is a single-phase device, and the PM flux reverses polarity when the mover advances one “small,” stator, pole (tooth). The two twin stators are displaced by one stator tooth also, to provide for optimal magnetic circuit completion. Large airgap PM flux densities of up to 1.25 T may be obtained under the stator teeth with 0.65 T left for armature reaction, to secure both high-force (power) density and a satisfactory power factor (or reasonable $IX/E = 0.5$ ratio; X = machine reactance). The PM height

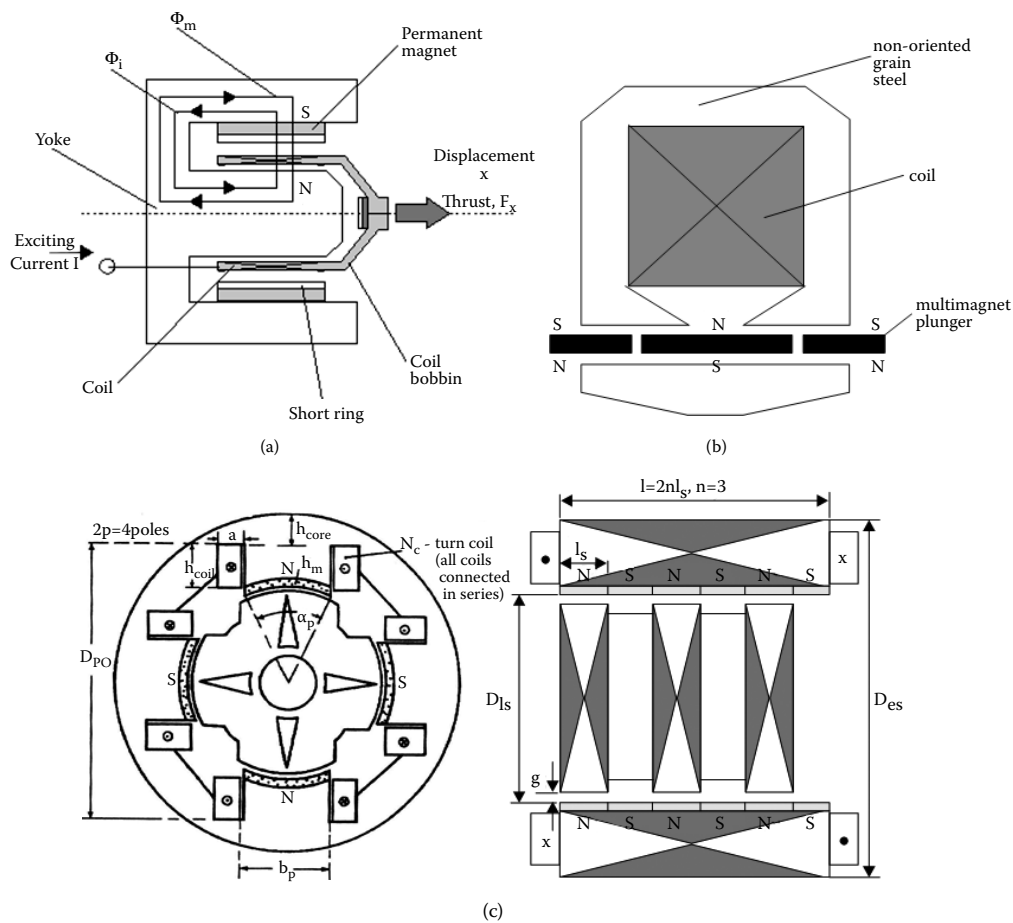


FIGURE 2.29 Commercial linear motion alternators: (a) with moving coil, (b) with moving permanent magnets (PMs), and (c) with moving iron.

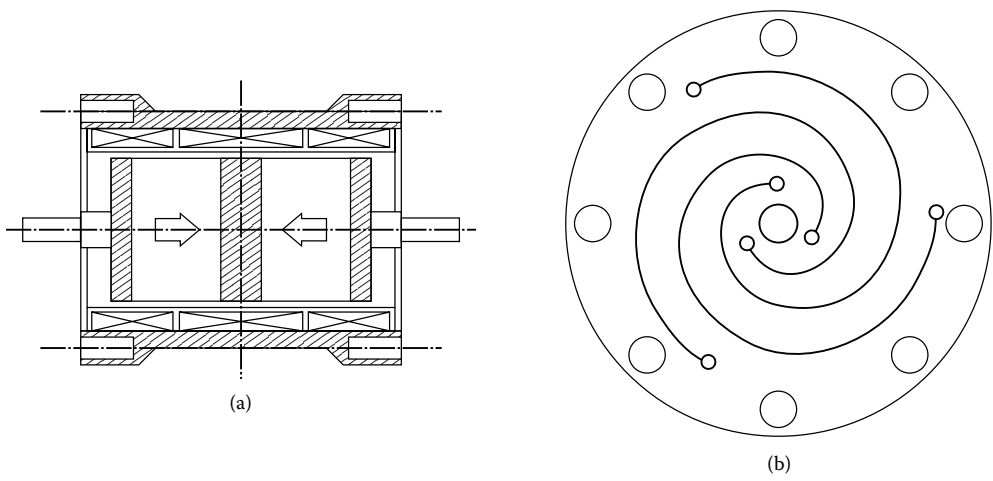


FIGURE 2.30 (a) Tubular linear motion alternator (LMA) and (b) with plunger supported on flexural springs.

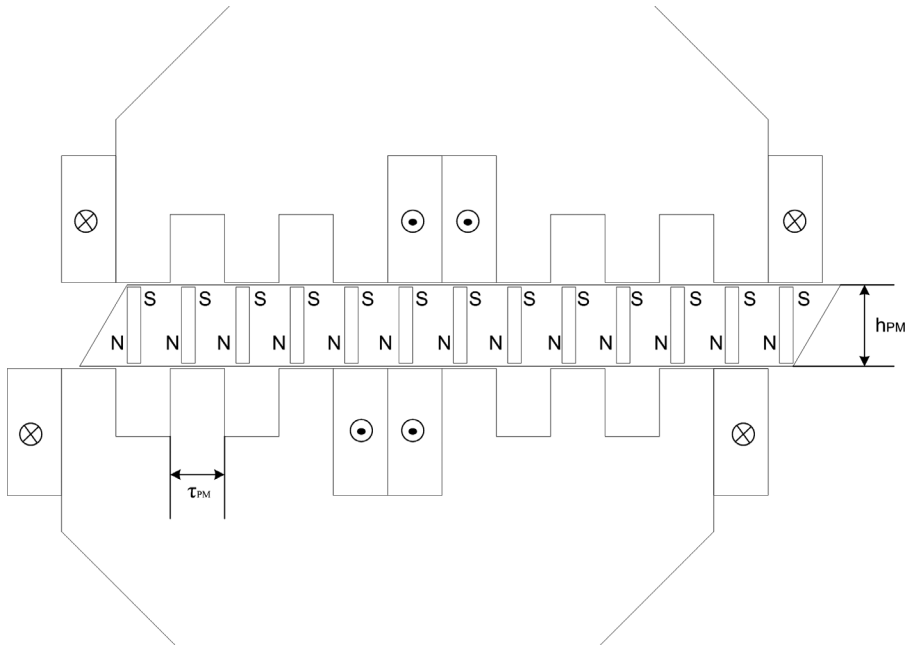


FIGURE 2.31 Flux reversal linear motion alternator (LMA) with mover permanent magnet (PM) concentration.

h_{PM} per pole pitch τ_{PM} is h_{PM}/τ_{PM} 1.5 – 2.5, as all PMs are active all the time, and full use of both stator and mover cores and copper is made.

Note that there are also LMAs that exploit progressive (rather than oscillatory) linear motion. Applications include auxilliary power LMAs on magnetically levitated vehicles (MAGLEVs) and plasma magnetohydrodynamic (MHD) linear motion DC generators with superconducting excitation (see Chapter 12 in *Variable Speed Generators*).

2.8 Electric Generator Applications

The application domains for electric generators embrace almost all industries, traditional and new, with powers from milliwatts to hundreds of megawatts per unit, and more [20–25].

Table 2.1 summarizes our view of electric generator main applications and the competitive types that may suit each person and need.

2.9 Summary

In this chapter, we presented some representative, in use and newly proposed, types of electric generators by principle, configuration, and application.

A few concluding remarks are in order:

- The power per unit range varies from a few milliwatts to a few hundred megawatts (even 1500 MVA) per unit.
- Large power generators, those above a few megawatts, are electrically excited on the rotor, either by DC, as in conventional synchronous generator (SG), or in three-phase AC, as in the wound rotor (doubly fed) induction generator (WRIG).
- While the conventional DC rotor-excited SGs require tightly controlled constant speed to produce constant frequency output, the WRIG may work with adjustable speed.

TABLE 2.1 Electric Generator Applications

Application	Large power systems (gas, coal, nuclear, hydrogen)	Distributed power systems (wind, hydro)	Standby diesel-driven EGs	Automotive starter-generators	Diesel locomotives
Suitable generator	Excited rotor synchronous generators, doubly fed induction generators (up to hundreds of MW/unit)	Excited rotor synchronous generators, cage-rotor induction generators, PM synchronous generators, parametric generators (up to 10 MW power/unit)	PM synchronous generators, cage-rotor induction generators	IPM synchronous generators, induction generators, transverse flux generators	Excited-rotor synchronous generators
Application	Home electricity production	Spacecraft applications	Aircraft applications	Ship applications	
Suitable generator	PM synchronous generators and LMAs	Linear motion alternators (LMAs)	PM synchronous, cage-rotor induction, or doubly fed induction generators (up to 500 kW/unit)	Excited synchronous generators (power in the order of a few MWs)	
Application	Small-power telemetry-based vibration monitoring	Inertial batteries	Super-high-speed gas-turbine generators		
Suitable generator	LMAs: 20–50 mW to 5 W	Axial-airgap PM synchronous generators up to hundreds of MJ/unit	PM synchronous generators up to 150 kW and 80,000 rpm (higher powers at lower speeds)		

- The rating of the rotor-connected PWM converter in WRIG is about equal to the adjustable speed range (slip), in general, around 20%. This implies reasonable costs for a more flexible generator with fast active and reactive power (or frequency and voltage) control.
- WRIG seems the way of the future in electric generation at adjustable speed for powers above a few megawatts, in general, per unit.
- PM synchronous generators are emerging for kilowatts, tenth of a kilowatt, and even hundreds of kilowatts or 1–3 MW/unit in special applications, such as automotive starter-alternators or super-high-speed gas turbine generators or direct-driven wind generators, respectively.
- Linear motion alternators are emerging for power operation up to 15 kW, even 50 kW for home or special series hybrid vehicles, with linear gas combustion engines and electric propulsion.
- Parametric generators are being investigated for special applications: switched reluctance generators for aircraft jet engine starter-alternators and transverse flux PM generators/motors for hybrid or electrical bus propulsion or direct-driven wind generators.
- Electric generators are driven by different prime movers that have their own characteristics, performance levels, and mathematical models, which, in turn, influence the generator operation, because at least speed control is enacted upon the prime mover. The next chapter discusses in some detail most used prime movers with their characteristics, mathematical models, and speed control methods.

References

1. T. Bödefeld, and H. Sequenz, *Elektrische Maschinen*, Springer, Vienna, 1938 (in German).
2. C. Concordia, *Synchronous Machines, Theory and Performance*, John Wiley & Sons, New York, 1951.
3. R. Richter, *Electrical Machines, vol. 2, Synchronous Machines*, Verlag Birkhäuser, Basel, 1963 (in German).
4. M. Kostenko, and L. Piotrovski, *Electrical Machines, vol. 2, AC Machines*, Mir Publishers, Moscow, 1974.
5. J.H. Walker, *Large Synchronous Machines*, Clarendon Press, Oxford, 1981.
6. T.J.E. Miller, *Brushless PM and Reluctance Motor Drives*, Clarendon Press, Oxford, 1989.
7. S.A. Nasar, I. Boldea, and L. Unnewher, *Permanent Magnet, Reluctance and Selfsynchronous Motors*, CRC Press, Boca Raton, FL, 1993.
8. D.C. Hanselman, *Brushless PM Motor Design*, McGraw-Hill, New York, 1994.
9. D.R. Hendershot Jr., and T.J.E. Miller, *Design of Brushless PM Motors*, Magna Physics Publishing and Clarendon Press, Oxford, 1994.
10. J. Gieras, F. Gieras, and M. Wing, *PM Motor Technologies*, 2nd ed., Marcel Dekker, New York, 2002.
11. I. Boldea, S. Scridon, and L. Tutelea, BEGA: Biaxial Excitation Generator for Automobiles, Record of OPTIM-2000, Poiana Brasov, Romania, vol. 2, pp. 345–352.
12. T. Miller, *Switched Reluctance Motors and Their Control*, Oxford University Press, Oxford, U.K., 1993.
13. Y. Liuo, and T.A. Lipo, A new doubly salient PM motor for adjustable speed drives, *EMPS*, 22, 3, 1994, pp. 259–270.
14. M. Radulescu, C. Martis, and I. Husain, Design and performance of small doubly salient rotor PM motor, *EPCS (former EMPS)*, vol. 30, 2002, pp. 523–532.
15. F. Blaabjerg, I. Christensen, P.O. Rasmussen, and L. Oestergaard, New advanced control methods for doubly salient PM motor, Record of IEEE-IAS-1996, pp. 786–793.
16. S.E. Rauch, and L.J. Johnson, Design principles of flux switch alternator, *AIEE Trans.*, 74, III, 1955, pp. 1261–1268.
17. H. Weh, H. Hoffman, and J. Landrath, New permanent excited synchronous machine with high efficiency at low speeds, In *Proceedings of the ICEM-1988*, Pisa, Italy, pp. 1107–1111.
18. G. Henneberger, and I.A. Viorel, Variable reluctance electric machines, Shaker Verlag, Aachen, 2001, Chapter 6.

19. L. Luo, S. Huang, S. Chen, T.A. Lipo, Design and experiments of novel axial flux circumferentially current PM (AFCC) machine with radial airgap, Record of IEEE-IAS-2001.
20. I. Boldea, and S.A. Nasar, Linear Electric Actuators and Generators, Cambridge University Press, London; New York, 1997.
21. J. Wang, W. Wang, G.W. Jewell, and D. Howe, Design and experimental characterisation of a linear reciprocating generator, *Proc. IEE*, vol. 145-EPA, 6, 1998, pp. 509–518.
22. L.M. Hansen, P.H. Madsen, F. Blaabjerg, H.C. Christensen, U. Lindhard, and K. Eskildsen, Generators and power electronics technology for wind turbines, Record of IEEE-IECON-2001, pp. 2000–2005.
23. I. Boldea, I. Serban, and L. Tutelea, Variable speed generators and their control, *J. Elec. Eng.*, vol. 2, no. 1, 2002 (www.jee.ro).
24. K. Kudo, “Japanese experience with a converter fed variable speed pumped storage system, *Hydropower & Dams*, March 1994.
25. T. Kuwabata, A. Shibuya, and M. Furuta, Design and dynamic response characteristics of 400 MW adjustable speed pump storage unit for Ohkawachi Power Station, *IEEE Trans.*, EC-11, 2, 1996, pp. 376–384.
26. T.-H. Kim, H.-W. Lee, Y.H. Kim, J. Lee, and I. Boldea, Development of a flux concentration-type linear oscillatory actuator, *IEEE Trans.*, MAG – 40, 4, 2004, pp. 2092–2094.